

**SUMMARY OF TOP QUARK PHYSICS \***

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I briefly review standard top quark physics at hadron colliders and summarize the contributions to this conference. The possibility of new mechanisms for  $t\bar{t}$  production are also discussed.

**1. Standard**

In hadron colliders the dominant mode of top quark production is via quark-antiquark annihilation or gluon-gluon fusion,

$$\begin{aligned} q \bar{q} &\rightarrow t \bar{t} \\ g g &\rightarrow t \bar{t}. \end{aligned}$$

However there are other modes,

$$\begin{aligned} W^+ g &\rightarrow t \bar{b} \\ W^{+*} &\rightarrow t \bar{b} \\ (\gamma, Z) g &\rightarrow t \bar{t} \\ (\gamma, Z)^* &\rightarrow t \bar{t} \\ &\dots \end{aligned}$$

In this list I have not included processes which pick a  $b$ -quark out of the hadron.

These processes are approximately ordered according to their rates in hadron colliders. Fig. 1(a) has the rates for the first three processes at the Tevatron assuming that the dominant decay model for the top quark is  $W^+ b$ . The channel, positron plus jets, was chosen so that the final state for all three processes is positron,  $b\bar{b}$  plus jets. The QCD,  $W$ -gluon and  $W^*$  processes have two, one and zero non- $b$ -quark jets, respectively.

Fig. 1(b) contains the QCD cross section for  $m_t = 175 \text{ GeV}$  versus  $\sqrt{s}$  for both proton-proton colliders and for proton-antiproton colliders. At  $\sqrt{s} = 1.8 \text{ TeV}$  the gluon-gluon fusion is only 10% of the cross section for a proton-antiproton collider, the

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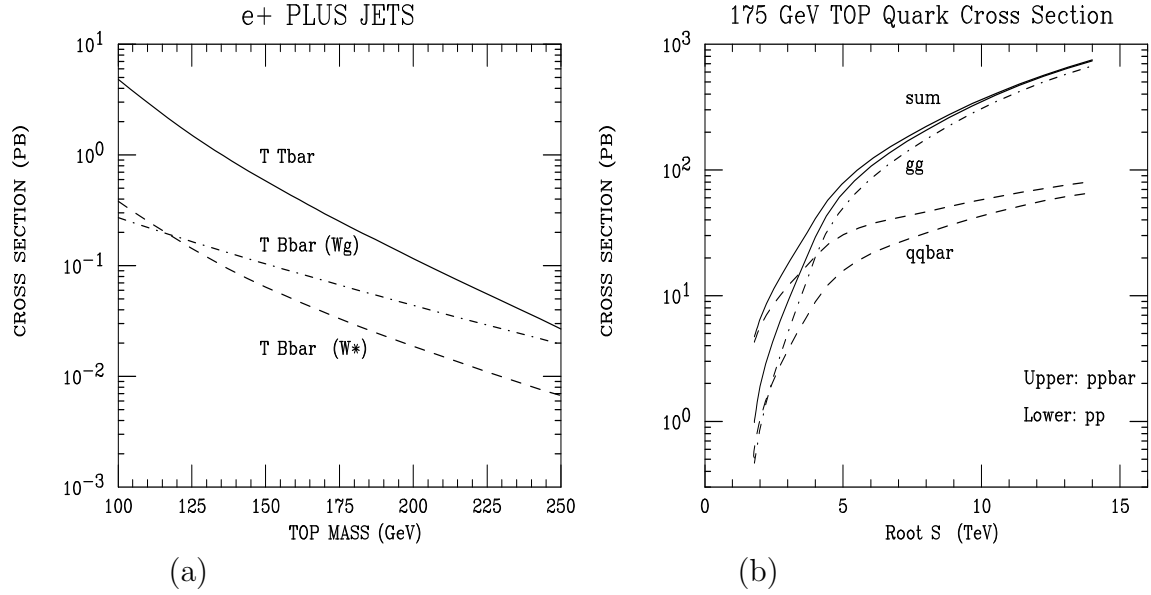


Fig. 1. (a) The Top Quark Production Cross Section at the Tevatron. The three curves are for quark-antiquark annihilation plus gluon-gluon fusion (solid), W-gluon fusion (dot-dash) and through an off-mass shell W-Boson (dashes). (b) QCD Top quark Production cross section as a function of  $\sqrt{s}$ , for quark-antiquark annihilation (dashes), gluon-gluon fusion (dot-dash) and the sum (solid) for both proton-antiproton (upper) and proton-proton (lower) colliders.

Tevatron, whereas at a 14 TeV proton-proton collider, the LHC, gluon-gluon fusion is 90% of the cross section.

For an accurate determination of the QCD top cross section, we need to consider the next to leading order calculations and the soft gluon resummation of the next to leading order calculations.<sup>1</sup> In Fig. 2, the results of these calculations using the same structure functions are shown. At high top quark masses the difference between these two calculations is at the 20% level.

The standard model decays of the top are

$$\begin{aligned}
 t &\rightarrow W^+ b \\
 t &\rightarrow W^+ (s \text{ or } d) \\
 t &\rightarrow g W^+ (b, s \text{ or } d) \\
 t &\rightarrow \gamma W^+ (b, s \text{ or } d) \\
 t &\rightarrow Z W^+ (b, s \text{ or } d) \\
 t &\rightarrow \phi W^+ (b, s \text{ or } d) \\
 &\dots
 \end{aligned}$$

For  $m_t = 175 \text{ GeV}$ , the total width of the top quark is approximately 1.5 GeV. The CKM suppressed decays are expected to be less than 0.1% of the non-suppressed decays. Whereas the decays including a Z or Higgs will be extremely small unless the on-mass shell decay is kinematically allowed.

Flavor changing neutral currents,

$$t \rightarrow (\gamma, g, Z \text{ or } \phi^0) + (c \text{ or } u),$$

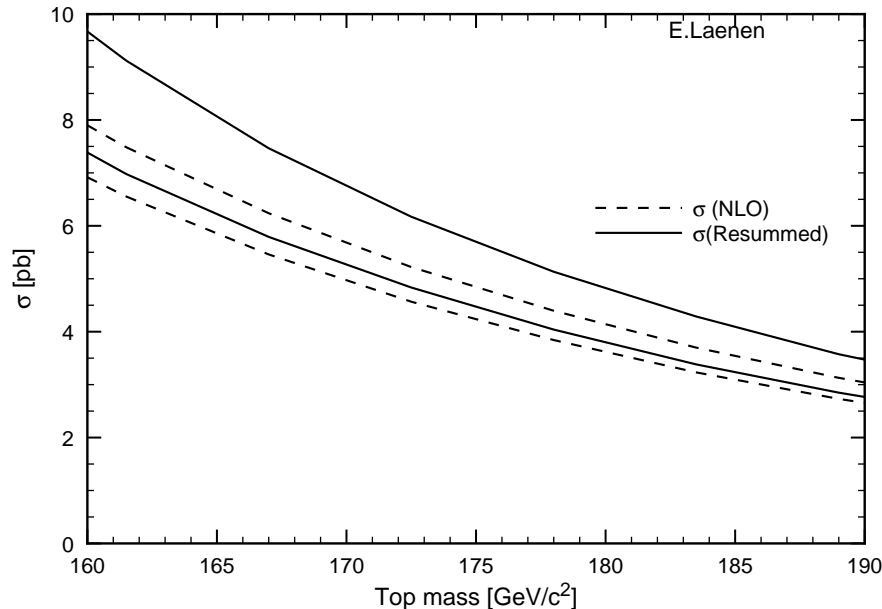


Fig. 2. The QCD Top Quark Production Cross Section at the Tevatron. The solid curves give the range of values using the resummed next to leading order calculations and the dashed curves are the range for the next to leading order calculations. The same structure functions were used.

have branching ratios less than  $10^{-10}$  in the Standard Model.

## 2. Searches

Both CDF<sup>2</sup> and D0<sup>3</sup> presented detailed results on the search for top at the Tevatron. The data presented included both the dilepton and the lepton plus jets mode for the decay of the  $t\bar{t}$  pair. However, neither collaboration presented data on the six jet mode. Theoretical calculations suggest that with an efficient  $b$ -quark tag, that this mode will be accessible at the Tevatron. A detailed summary of the experimental results present can be found in the review of hadron collider physics by Shochet.<sup>4</sup>

CDF observes a  $2.8\sigma$  (0.26%) effect which is not sufficient to firmly establish the existence of top but which, if interpreted as top, yields  $m_t = 174 \pm 10^{+13}_{-12} \text{ GeV}/c^2$  and  $\sigma_{t\bar{t}} = 13.9^{+6.9}_{-4.8} \text{ pb}$ .

D0 does not observe a significant excess of events due to  $t\bar{t}$  production. The probability for the background to fluctuate to give greater than or equal to the observed number of events is 7.2% ( $1.5\sigma$ ). If  $m_t = 180 \text{ GeV}$  then  $\sigma_{t\bar{t}} = 6.5 \pm 4.9 \text{ pb}$ .

Orr<sup>5</sup> presented the results of a study on the effects of soft gluon radiation in the determination of the top quark momentum. The results of this study will be important for precision measurements of the top quark mass at hadron colliders.

## 3. Surprises

In the Standard Model the couplings of the top quark to each of the gauge bosons,  $g, \gamma, Z$  and  $W^\pm$ , are determined, including radiative corrections. Therefore potential new physics could show up as deviations of these vertices from Standard Model expectations. Kao<sup>6</sup> and Rizzo<sup>7</sup> discussed corrections to the QCD coupling,  $gt\bar{t}$ . Kao's paper concentrated on the one-loop weak corrections in both the Standard Model and the

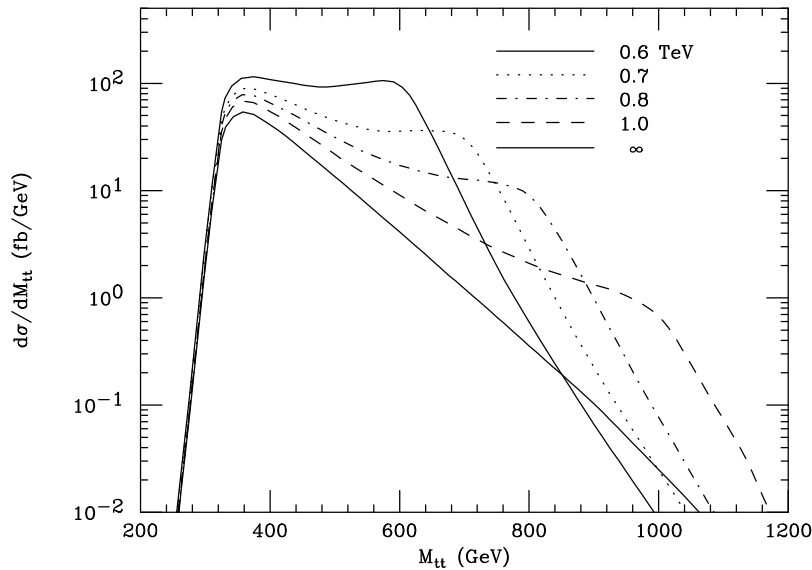


Fig. 3. The differential distribution,  $\frac{d\sigma}{dM_{t\bar{t}}}$  versus  $M_{t\bar{t}}$  for top-antitop production with the curves labelled by the mass of the octet top-color vector boson.

Minimal Supersymmetric Standard Model. Whereas Rizzo considered the effects of an anomalous chromomagnetic moment to this coupling.

Schmidt<sup>8</sup> summarized top quark physics at  $e^+e^-$  colliders and in particular discussed the signatures of deviations to the  $\gamma t\bar{t}$ ,  $Z t\bar{t}$  and  $W t\bar{b}$  vertices at such machines.

Of course the top quark could present more dramatic surprises such as charged Higgs decays,  $t \rightarrow H^+ b$ , large flavor changing neutral current decays,  $t \rightarrow (g, Z \text{ or } \gamma) + (c \text{ or } d)$  or enhanced production through a new resonance. This latest possibility could occur either through the quark-antiquark production mode,<sup>9</sup> as expected in Top-color models of electroweak symmetry breaking or via the gluon-gluon fusion<sup>10</sup> as suggested by some Technicolor models. In both cases the  $t\bar{t}$  pair is produced by the decay of a heavy new particle, Top-color Boson or Techni-eta, which distorts the  $P_T$ ,  $\cos\theta^*$  and  $M_{t\bar{t}}$  distributions from the Standard Model expectation. Fig. 3 is the change in the shape of the  $M_{t\bar{t}}$  distribution in the Top-color Model discussed by Hill and Parke.<sup>9</sup> We should think of top quark production as a new Drell-Yan process probing extremely high mass scales, greater than 500 GeV.

#### 4. Conclusion

The top quark is an exciting new window on very high mass scale physics. While exploring the vista from this window we should be on the lookout for any deviation from the Standard Model which will provide us with information about that elusive beast, the mechanism of electro-weak symmetry breaking. Because the mass of the top quark is very heavy, this quark is the particle most strongly coupled to the electro-weak symmetry breaking sector. Therefore the deviations could be seen at zeroth order or may require more subtle measurements.

What is needed is hundreds of top-antitop pairs as soon as possible. Then, watch out for surprises at DPF'96!

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